

Vibration Isolation System for the Stratospheric Observatory for Infrared Astronomy (SOFIA)

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ABSTRACT

The subject of this paper is the Vibration Isolation System for the Stratospheric Observatory for Infrared Astronomy, SOFIA. Included are discussions of the various concepts, design goals, concerns, and the proposed configuration for the Vibration Isolation System.

INTRODUCTION

NASA - Ames Research Center has recently completed a phase A feasibility study for the Stratospheric Observatory for Infrared Astronomy (SOFIA), an advanced airborne astrometric facility. (See Figure 1.) SOFIA will consist of a three meter F1 telescope mounted in a Boeing 747SP aircraft. The technology for the system will be an extension of that used for the Kuiper Airborne Observatory (KAO), a 0.9 meter (36 inch) diameter F1.8 telescope mounted in a C141 aircraft that has been highly successful in infrared astronomy for the past ten years.

Infrared astronomy involves the study of the spectrum of electromagnetic radiation between the wavelengths of 0.3 to 1200 micrometers from celestial bodies in the universe. Unfortunately, a large portion of the infrared spectrum is not visible at ground level due to absorption by water vapor, carbon dioxide and molecular oxygen which lie between the ground and 12 kilometers (40,000 ft). Therefore, it is highly desirable for infrared astronomers to make observations at altitudes above the tropopause which is an inversion layer located generally between 12 and 13 kilometers (39,000 to 41,000 feet). Approximately 99% of the moisture in the atmosphere is contained below this layer. SOFIA will be designed to fly for extended periods of time above these altitudes.

SYSTEM CONFIGURATION

The telescope structure will be located in an open cavity between two full depth bulkheads at body stations 520 and 700 on the Boeing 747SP. (See Figure 2) The optical axis will be located at body station 600. The cavity has an opening on the port side of the aircraft that allows the telescope to point from a 20 degree elevation angle to a 60 degree elevation angle. There is also a ± 4 degrees freedom of rotation in cross elevation and line of sight. The estimated weight of the complete floating telescope structure is approximately 13,600 kg (30,000 lb).

Once the telescope is oriented to the desired tracking position, infrared

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images are reflected through the Cassegrain telescope, then redirected by a tertiary mirror to pass along the optical tube, through the aft bulkhead to the experimenter instrument package. (See Figure 2)

Since the objects of interest are essentially at infinity, pure rigid body displacements of the telescope do not affect the image quality. However, rotations do have an effect and any angular displacements must be minimized to obtain good image quality. During tracking the telescope structure is floated on a spherical air-bearing/stator-ring assembly. The spherical air bearing is located at the center of mass of the telescope system and is part of the structural interface between the telescope structure and the instrument-package and counter-weight structure. The thin layer of air that flows over the spherical surface of the air bearing allows for isolation of the three rotational degrees of freedom of the telescope from the aircraft by providing nearly frictionless rotation. In order to achieve this isolation it is required that the center of gravity of the "floated" assembly be located at the center of rotation of the air bearing. This centering is accomplished by controlling the amount and position of counter weights applied on the cabin side of the telescope. Ideally, due to the frictionless behavior of the air bearing, no torque would be required to maintain tracking. However, there are several factors which require the use of reaction torques to prevent telescope rotation: aerodynamic loading, a slightly offset center of mass, cable loads, motion or mass changes within the instrument, or the small amount of friction that does exist. The torquers used for these corrections are also used to position the telescope and to provide the nod (telescope sweeping) required for infrared astronomy.

The torquer system consists of three orthogonal sets of electromagnetic arc shaped segments which are attached to the telescope structure with a corresponding segment attached to the stator of the air bearing. Because the only physical connection between the floating telescope system and the stator is a magnetic force across an air gap, the torquers are allowed to be completely frictionless when they are not in use. Each torquer has a range of plus or minus four degrees. In addition, the elevation angle torquer is in series with a spur gear to provide the total elevation range of the telescope system of 20 to 60 degrees. The design goal of the torquers in conjunction with the pointing and control system is to maintain a tracking position with a maximum error of one arcsecond.

Finally, the stator of the air bearing is supported by the Vibration Isolation System which ties directly to the aft bulkhead. Although pure translation of the telescope does not contribute to image degradation, the effects of translational accelerations, which can include angular displacements or telescope structural distortions, are undesirable and therefore must be minimized to obtain optimum image quality. The Vibration Isolation System will act to attenuate aircraft vibrations from the telescope in the three translational directions in order to maintain the desired image quality. This system will be described in the next section of this paper.

VIBRATION ISOLATION SYSTEM

The primary design goal of the SOFIA Vibration Isolation System is to

minimize image distortion during tracking. This can be accomplished by first analyzing the telescope structure natural frequencies and aircraft/airframe structure vibrations, and then choosing the natural frequency and damping characteristics of a vibration isolation system that minimizes image distortion.

Another important design requirement is that the vibration isolation system must prevent damage to the telescope during gusts and turbulence, as well as during takeoff or landing. To avoid excessive displacement and still allow for these types of loadings requires the use of a dual mode isolation system. These modes include the "tracking" mode which maintains a low natural frequency to maximize vibration attenuation, and the "caged" mode which still provides attenuation, but with stiffer springs to limit the maximum displacement of the floating structure. Additional system design goals include, high reliability, low weight, minimum power consumption and low or no maintenance. Since this is an infrared telescope that is cooled to the outside ambient temperature, heat sources and heat paths must also be minimized or eliminated.

Among the concepts initially considered were metal springs, elastomeric/composite pads and pneumatic isolators. Reviewing the requirements and the advantages and disadvantages of each concept leads to the choice of pneumatic isolators. Metal springs were not feasible due to their large static deflection for the weight and frequency requirements. Composite or rubber pads in general have natural frequencies between 5 and 10 Hz for the size required to carry the load, and would therefore act as amplifiers rather than isolators in the critical frequency range making them infeasible.

Pneumatic isolators were chosen because of their ability to attenuate low frequency vibration. This type of isolator can be designed to have both low stiffness and low static deflection, due to the ability of the air to be compressed to the pressure necessary to support the system load. The pneumatic isolator can be designed as a simple spring, having only one chamber for compressed air. Alternately, by having two chambers connected by a variable orifice, the pneumatic isolator can become a tuneable spring damper. The tunability will be discussed later in this report.

In designing the vibration isolation system it was assumed 1) that the center of mass of the telescope structure will be located at the center of the air bearing and 2) that the isolators will be mounted in a vertical plane also passing through the center of the air bearing. This configuration decouples the modes of vibration and allows the system to be analyzed as a single degree of freedom system in each of the three translational directions.

AIRCRAFT RESPONSE

In order to begin design of the Vibration Isolation System, it was necessary to estimate the vibration that would be transmitted to the isolation system from the aircraft. The first estimates were based on the actual aircraft power spectral density (PSD) plots provided by Boeing. These plots were provided for several locations throughout the aircraft for various

flight conditions. Vibration analysis for SOFIA was based on the Boeing PSD plot for body station 310 at an altitude of 40,000 ft. and a speed of $M=0.8$, this data being the closest to the proposed isolation system location and flight conditions for SOFIA during tracking.

Because the PSD's were random plots, a cubic spline curve fitting was performed to generate continuous functions representative of the PSD's in the lateral and vertical directions. The area under the PSD curve represents the variance (square of the standard deviation) of the probability distribution curve for the random vibration. For a single degree-of-freedom system, the mean square response of the structure to a random excitation is the integral of the product of the PSD and the complex frequency response for the structure. The value resulting from the square root of the integration is multiplied by a peak response factor of 3 to account for 99.7% of the random vibrations based on a Gaussian probability distribution. The resulting RMS accelerations were plotted versus natural frequencies for damping factors of 1%, 2%, 5% and 10%. (See Figure 3.) Using these plots, optimal design frequencies were determined for the lateral and vertical directions. These plots show that the isolation system should have resonant frequencies of 1 Hz and 1.5 Hz in the vertical and lateral directions, respectively, in order to provide optimum attenuation of vibration for the Boeing 747SP.

As explained above, preliminary optimum natural frequencies for the Vibration Isolation System were determined on the basis of standard flight condition data supplied by Boeing. However, SOFIA will be subjected to additional non-standard flight conditions (for which no vibration data exists) namely, the effects of opening the cavity and raising the boundary-layer control fence. Moreover, since a modified 747 does not exist, the tracking mode vibration levels could not be measured. To determine these effects, vibrational data was collected on the Kuiper Airborne Observatory. The data was recorded to establish a correlation between the vibration on the aircraft near the telescope in "standard flight mode", with the cavity door closed and the boundary-layer control fence down, to that in the "tracking mode" with the cavity door open and the boundary-layer control fence up. PSD's were recorded in three locations, below the two rear isolators on the airframe and directly on the left rear isolator. It was found that below 30 Hz the effect of opening the telescope door was very minor. In this frequency range there was an increase in the magnitude of the vibrations by a factor less than 10. Between 30-55 Hz and 80-100 Hz, vibrations during tracking increased approximately 10 times over that of standard flight vibrations. The largest increase occurred between 60-80 Hz where there was a factor increase as large as 60. Opening the cavity resulted in a PSD nearly equivalent to that for white noise. Based on this data and for simplification of analysis, a conservative level of white noise was assumed. The increase in vibration caused by opening the cavity door and raising the boundary-layer control fence could then be determined.

To obtain an estimate for the vibration of the 747SP with a cavity door open, the square root of the areas under the Boeing 747SP PSD's was calculated to first determine the RMS g accelerations for that aircraft during normal flight at 12.2 kilometers (40,000 ft) and a speed of 0.8 Mach. These accelerations were then multiplied by the square root of the ratio of

[door open] to [door closed] vibrations measured on the KAO to determine the estimated RMS accelerations that will be transmitted to the vibration isolation system on the 747SP during tracking. It should be noted that no information was provided for the fore/aft levels of vibration for the 747SP. Therefore, the fore/aft vibrations were assumed to be the same as the lateral vibrations based on the data collected on the C141.

The resulting estimated magnitudes of vibration experienced during tracking on the 747SP were found to be approximately 0.21 g's vertically and 0.14 g's in the lateral and in the fore/aft directions. (See Figure 4.) Because these values were lower than the specified flight conditions outlined in the SOFIA project requirements, the isolation system was designed to meet the original SOFIA specifications. These specifications require designing to a maximum acceleration during tracking of 0.25 g's in all directions. The maximum gust/maneuvering loads, when the system is in the "caged" mode, are 3.04 g's upward and 1.04 g's downward, ± 0.63 g's in the lateral and ± 0.20 g's in the fore/aft direction. One final criterion for the vibration isolation system is to survive the crash loads. The crash loads are 4.5 g's upward, 2.0 g's downward, ± 1.5 g's laterally, 9 g's forward and 1.5 g's aft. The criteria for crash loads require that the system not come free in the aircraft. Damage to the system, however, is acceptable for crash loads.

PROPOSED SYSTEM

The proposed vibration isolation system consists of eight pneumatic isolators all located in a plane parallel to the aft cavity bulkhead and acting through the mass center of the telescope system. (See Figure 5.) Four of the pneumatic isolators will be aligned in the vertical plane passing through the mass center. In the tracking mode these four isolators will need to carry the dead weight of the floating telescope structure. These will be semi-active in their axial directions, and a height control valve will be used to react any input displacements by permitting air to transfer to/from the surge tank when a displacement occurs. Also, internal snubbers are to be connected in series with these isolators. When the system is active, these snubbers minimally affect the system stiffness, however when the system is lowered or caged, they provide the primary vibration isolation. The additional four pneumatic springs will be connected at the same locations as the first isolators, but will be aligned in the fore/aft direction. The total system stiffness in each of the three translational directions is, therefore, a combination of the stiffness of the lateral and vertical pneumatic isolators and the internal snubbers.

As mentioned previously, the proposed isolation system will have two modes of operation, the "tracking" mode and the "caged" mode. In the first mode, the isolators will have natural frequencies of about 2.5 Hz up to a maximum acceleration of 0.25 g's. If the 0.25 g limit is reached, the isolators will enter the locked mode where the internal snubbers will provide vibration isolation at a stiffer natural frequency of about 7 Hz. These internal snubbers will restrict deflections up to the maneuvering/gust limit load. If the acceleration reaches the level of the crash limit loads, the external snubbers will prevent metal-to-metal contact.

The maximum deflection of the system for each mode of operation is

based on the total stiffness of the isolators and the maximum acceleration in that mode. When the system is "caged", the pneumatic isolators act as rigid supports and deflection is governed by the stiffnesses of the internal snubbers. In this mode the system is designed to the gust/maneuvering limit load, this is also the mode to react the crash loads. The maximum deflection in any mode is limited by external snubbers to a maximum displacement of one inch. (See Figure 5.)

The design of the isolators will incorporate relaxation damping principles in the "tracking" mode. The system consists of compressed air flowing from a surge tank into a load-carrying chamber through an orifice which acts as a capillary flow restrictor. The size of the orifice will determine the amount of system damping as well as the stiffness and natural frequency of the system. This in turn controls the magnitude of vibration transmitted to the telescope.

By varying the orifice size, the system's damping factor, as well as its natural frequency, can be controlled. The system can then be adjusted or tuned to an optimum response. Small variations in the orifice can result in pronounced variations in resonant frequency. When the orifice is small, flow is highly restricted and the system characteristics (i.e. natural frequency and stiffness) will be determined by the pressure and volume in the load carrying chamber. For a large orifice the restrictions are lowered and the system characteristics are determined by the pressure and volume of both the surge tank and the load carrying chamber. By using a variable orifice in the design, an optimum orifice size can be determined upon installation based on actual aircraft response. (See Figure 6.)

Once the system damping requirements are determined, the accelerations transmitted through the isolators to the telescope can be found based on the input level of vibration and the system natural frequency. For example, a 2.5 Hz critically damped isolation system will transmit 0.065 g's in the lateral fore/aft directions and 0.098 g's vertically (based on the Boeing PSD's.) The resulting deflections during tracking will be 0.38 cm (0.15 in.) vertically and 0.26 cm (0.10 in.) in their lateral and fore/aft directions, based on the system stiffness and input accelerations.

CONCERNS AND RISKS

While basic feasibility of a candidate concept has been demonstrated, several areas which require further analysis and trade-off activity still exist for the SOFIA vibration isolation system. In the area of aircraft response, new 747SP PSD's should be measured at approximately body station 700, with additional fore/aft data included. The data provided by Boeing is somewhat suspect; one would expect lower vibration levels for a 747SP than for the C141 (KAO). From our measured data this is not the case. It is suggested that additional vibration data be collected for an unmodified 747SP which would address the added requirements.

The effect of a slightly offset center-of-mass, which would affect the response of the isolators, needs to be evaluated. Also of concern is the fact that the current design has the torquers reacting through the vibration isolation

system. This not only affects the torquer response, but could also couple together translations and rotations.

A final trade-off study that should be performed in greater depth is the "soft system versus stiff system" problem. There is a trade-off between minimizing response to aircraft vibration, (where a soft system is more advantageous), to minimizing response to aero loads (where a stiff system would be better). The resolution of the problem depends on the relative levels of structure-borne versus aero-generated loading. The aero loading on the telescope is largely unknown at present and depends on several factors. It is, therefore, a good candidate for near-term analysis or testing.

PROJECT STATUS

The Phase A study has been completed and has demonstrated feasibility. Currently, the project is awaiting additional funding for further studies.

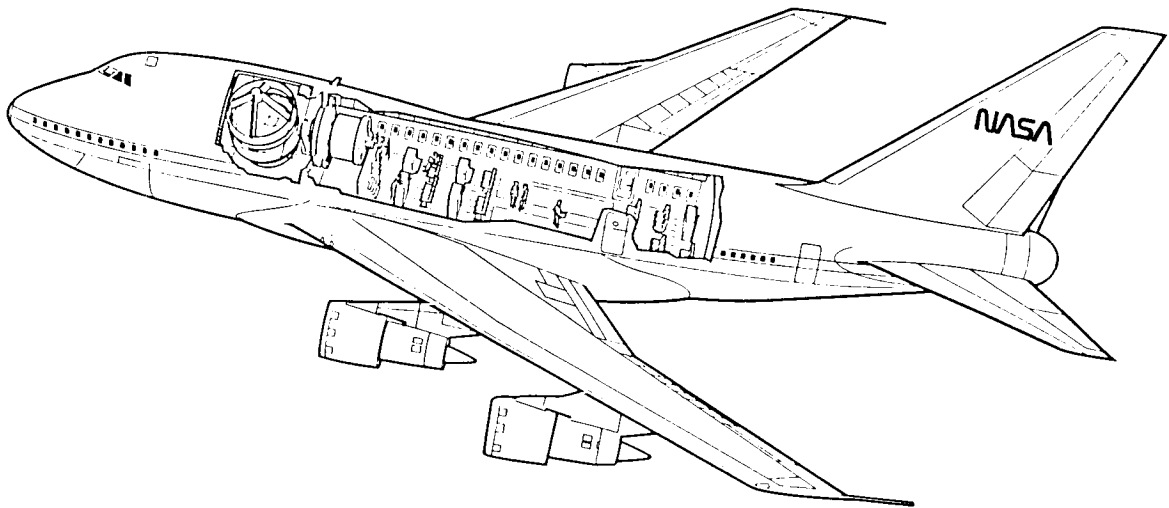


Figure 1. Stratospheric observatory for infrared astronomy.

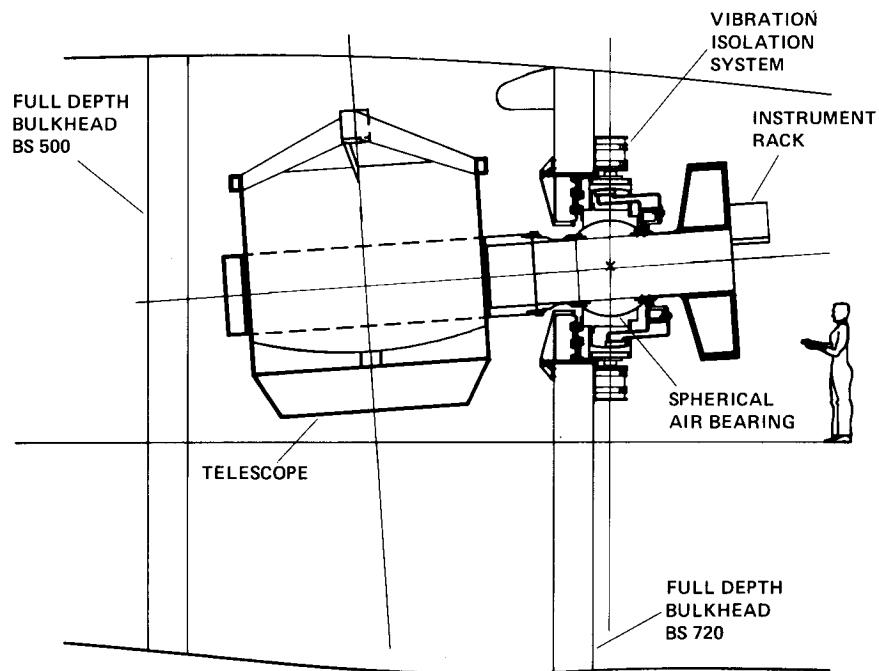


Figure 2. Stratospheric observatory for infrared astronomy.

$$F^2(t) = [H(f)H^*(f)] S(f) df$$

$$F(t) = \sigma [F^2(t)]$$

WHERE:

$F^2(t)$ = MEAN SQUARE RESPONSE OF THE STRUCTURE TO A RANDOM EXCITATION (g^2)

$F(t)$ = RMS MEAN ACCELERATION

σ = PEAK RESPONSE FACTOR (PROBABILITY OF $F(t)$)

$S(f)$ = POWER SPECTRAL DENSITY FUNCTION (g^2/Hz)

$[H(f)H^*(f)]$ = COMPLEX FREQUENCY RESPONSE FUNCTION FOR THE STRUCTURE (SINGLE DEGREE OF FREEDOM)

WHERE:

$$H(f) = \frac{1}{[1 + (f/f_n)^2] - i[2\xi(f/f_n)]}$$

$$H^*(f) = \frac{1}{[1 - (f/f_n)^2] - i[2\xi(f/f_n)]}$$

f_n = NATURAL FREQUENCY OF STRUCTURE (Hz)

ξ = DAMPING COEFFICIENT

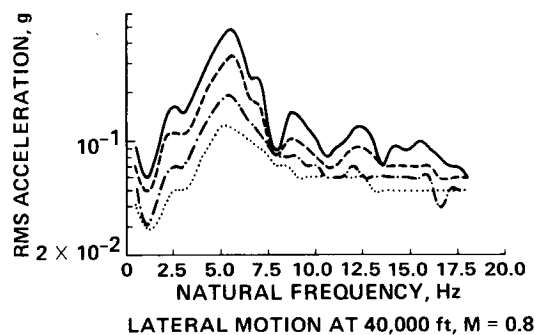
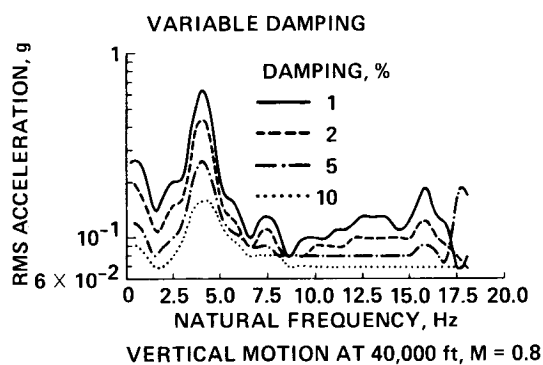


Figure 3. Structural response to random vibration.

	RATIO TRACKING DOOR CLOSED, g^2/g^2	AREA UNDER PSD CURVE NORMAL FLIGHT, g^2	RMS ACCELERATION NORMAL FLIGHT, g	RMS ACCELERATIONS DURING TRACKING, g
C141¹ (0-100 Hz)				
VERTICAL	17	0.00012	0.011	0.045
LATERAL	14	0.00032	0.018	0.067
FORE/AFT	45	0.00008	0.0089	0.067
BOEING 747SP (0-20 Hz)				
VERTICAL	20 ⁴	0.0022	0.047	0.21 ²
LATERAL	15 ⁴	0.0013	0.036	0.14 ²
FORE/AFT ³	—	—	—	0.14 ³

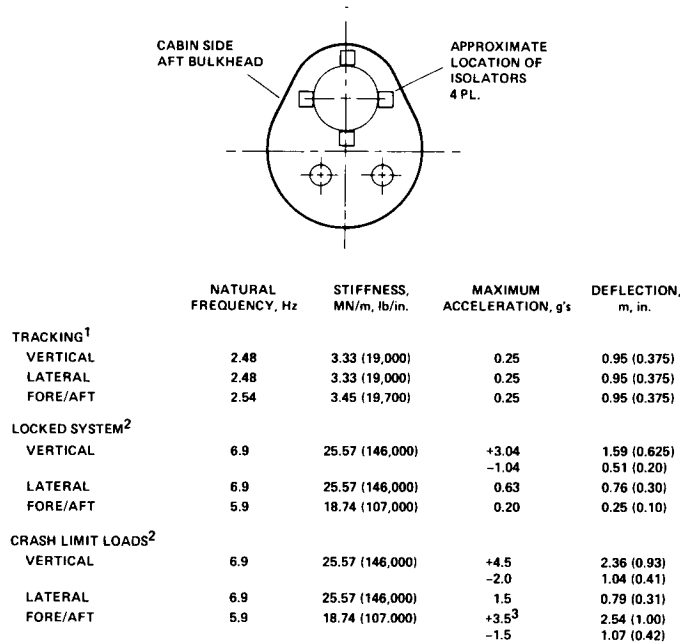
¹VALUES BASED ON ACTUAL TEST DATA TAKEN ON THE KAO

²ESTIMATED ACCELERATION FOR 747SP = (NORMAL FLIGHT ACCELERATIONS) X (TRACKING/DOOR CLOSED RATIO)^{1/2}

³NO FORE/AFT DATA WAS PROVIDED BY BOEING FOR THE 747SP IN THE FORE/AFT DIRECTION; LATERAL AND FORE/AFT ACCELERATIONS ASSUMED EQUAL BASED ON C141 DATA

⁴RATIO OF TRACKING/DOOR CLOSED VIBRATIONS FOR 747SP IS ASSUMED EQUIVALENT TO THAT FOR THE C141

Figure 4. Boeing 747SP estimated vibrational accelerations.

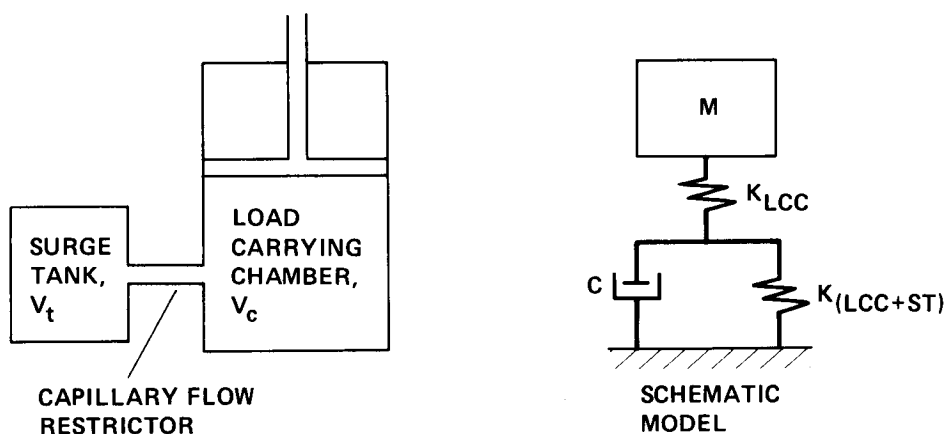


¹STIFFNESS AND NATURAL FREQUENCY DETERMINED BY PNEUMATIC ISOLATORS, AIR SPRINGS AND INTERNAL SNUBBERS

²STIFFNESS AND NATURAL FREQUENCY DETERMINED BY AIR SPRINGS AND INTERNAL SNUBBERS

³MAXIMUM FORWARD CRASH LOAD IS 9 g's; EXTERNAL SNUBBERS MINIMIZE MOTION BEYOND 1" DEFLECTION AND 3.5 g's (FORWARD DIRECTION)

Figure 5. Proposed vibration isolation system.



ORIFICE SIZE DETERMINES DAMPING

SMALL ORIFICE – HIGH RESTRICTION

$$C = \infty \quad K = 2nPA^2/V_c = K_{LCC}$$

LARGE ORIFICE – LOW RESTRICTION

$$C = 0 \quad K_0 = 2nPA^2/(V_c + V_t) = [(K_{LCC})(K_{ST})]/[K_{LCC} + K_{(LCC+ST)}]$$

WHERE:

C = DAMPING CONSTANT

K = ISOLATOR STIFFNESS

$n = 1.4$ FOR COMPRESSED AIR

P = PRESSURE IN CYLINDER

V_c = LOAD CARRYING CHAMBER VOLUME

V_t = SURGE TANK VOLUME

A = PISTON AREA

Figure 6. Damped pneumatic isolators.